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Probing CPT violation with atmospheric neutrinos

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ABSTRACT

We investigate the recently suggested scheme of independent mass matrices for neutrinos and antineutrinos. Such a CPT violating scheme is able to account for all neutrino data with the three known flavors. For atmospheric neutrinos this means that it is possible to have different mass-squared differences driving the oscillation for neutrinos and antineutrinos. We analyse the atmospheric data within the simplest scheme of two neutrino oscillation, neglecting electron neutrino oscillation. The antineutrino mass-squared difference is preferred to be larger than 0.1 eV^2 while the neutrino mass-squared difference should be around 10^{-3} eV^2. In this parameter region the atmospheric data are independent of the antineutrino mass-squared difference. Therefore no constrain can be put on CPT violation effects contributing to different masses for the neutrinos and antineutrinos.

1 Introduction

Many elementary particles, like the electron and the kaons, have tight bounds on possible CPT violating effects contributing to different masses for the particle and its antiparticle. For instance for the electron and the positron we have [1]

$$\frac{m_{\mathrm{e}^+} - m_{\mathrm{e}^-}}{m_{\mathrm{average}}} < 8 \times 10^{-9} \,, \qquad \mathrm{CL} = 90\% \,. \tag{1}$$

The atmospheric neutrino data involve both the particle and the antiparticle channel and is therefore suitable for a study of possible CPT violation in the neutrino sector. Naturally as the atmospheric neutrino experiments are probing mass-squared differences and not the absolute neutrino mass, this will be the quantity which might be restricted by the data. The interest in CPT violation arises due to the recent suggested scheme by Yanagida and Murayama, which is capable of solving all neutrino anomalies without the use of a light sterile neutrino.

At present three neutrino anomalies (atmospheric [2], solar [3] and LSND [4]) exist, all requiring different Δm^2's when interpreted in terms of neutrino oscillation. Therefore a CPT conserving three neutrino framework cannot account for all anomalies. This has also been explicitely shown by fitting to atmospheric data [5, 6]. Consequently one is forced to go beyond standard explanations to solve all anomalies.

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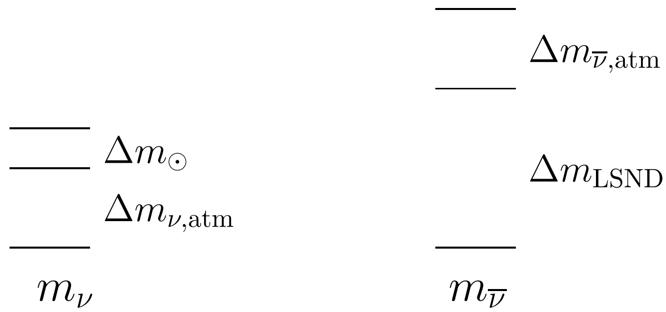

Figure 1: Schematically view of the masses of neutrinos and antineutrinos

A possible solution could be the existence of a light sterile neutrino. Several studies of such four neutrino models has been performed and the current situation has been presented in Ref.[7]. Although the four neutrino models do have an acceptable goodness of fit when fitting to all available data, each of the different solutions faces problems with a particular subset of the data. The '3+1' mass spectra is in disagreement with the short-baseline experiments and the '2+2' mass spectra is in conflict with either the atmospheric or the solar neutrino data. Therefore the four neutrino models cannot be excluded at present but they nevertheless seems disfavored.

In the absent of a sterile neutrino Yanagida and Murayama [8] has recently suggested another possibility to solve all of the known neutrino anomalies. This Yanagida-Murayama model involve CPT violation by invoking independent masses for neutrinos and antineutrinos, giving a total of four independent Δm^2's. Schematically we can represent the masses for the neutrino and antineutrino as in Fig.1. The solar neutrino problem is only concerning the disappearance of ν_e and the LSND experiment sees $\overline{\nu}_e$ appearance from a $\overline{\nu}_\mu$ beam. These experiments can be separately solved by $\Delta m^2_\odot$ and $\Delta m^2_{\mathrm{LSND}}$ in the Yanagida-Murayama model. The atmospheric neutrinos data includes both ν_μ and $\overline{\nu}_\mu$ and the two Δm^2's is no longer constrained to be identical. It is therefore clear that all the data can be explained within this model.

To bring about CPT violation might seem like a drastic step to take. However different mechanisms for creating CPT violation in the neutrino sector has been suggested [9]. Such a mechanism could for instance arise from string theory via the extra dimensions. The right-handed neutrinos, like the graviton, are free to travel in the bulk, whereas the Standard model fields are all constrained within a four dimensional brane. This gives rise to non-locality for the neutrinos and hereby provoking CPT violation. The CPT violating scheme is also able to account for baryogenesis in a natural way [9].

The atmospheric neutrino problem is by now well established and can be accounted for by a two neutrino $\nu_\mu \to \nu_\tau$ oscillation [2], although sub-dominant oscillation are possible and maybe even welcome. In this paper we will study the atmospheric neutrino anomaly within a two generational neutrino scheme with CPT violation. The electron neutrinos are assumed not to oscillate on the atmospheric scale. Having different mass matrices for neutrinos and antineutrinos naturally gives different mixing matrices; U_ν for the neutrino sector and $U_{\overline{\nu}}$ for the antineutrino sector. We will investigate whether restrictions can be put on these mixing parameters from the atmospheric neutrino data. The most interesting parameter is perhaps the difference in mass-squared difference for neutrinos and antineutrinos. Let us define the parameter ϵ to describe the amount of CPT violation

$$\epsilon = |\Delta m^2_{\nu,\mathrm{atm}} - \Delta m^2_{\overline{\nu},\mathrm{atm}}| \ . \tag{2}$$

Naively one might expect that ϵ is bounded from above [10]. However, using the latest data, we will show that no such bound exist.

Let us finally mention that the LSND experiment which has not been confirmed is intended to be tested by the Mini-BooNE experiment [11]. However, as already noticed, unless they run in the antineutrino channel, they can not rule out the Yanagida-Murayama model.

2 Analysis of the atmospheric data

There exist a number of experiments having measured the atmospheric neutrino fluxes. Here we will only consider the contained events of the Super-Kamiokande (SK) experiment [12]. The justification for leaving out other data sets is that the statistics of the Super-Kamiokande data is in any case superior. Furthermore, as will be discussed below, the high energy upward through-going muon events [13] are less affected by antineutrinos.

We use the simple two generational probability formula for neutrinos

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2(2\theta_\nu) \sin^2\left(\frac{L\Delta m^2_\nu}{4E}\right) \tag{3}$$

and for antineutrinos,

$$P_{\overline{\nu}_\mu \to \overline{\nu}_\mu} = 1 - \sin^2(2\theta_{\overline{\nu}}) \sin^2\left(\frac{L\Delta m^2_{\overline{\nu}}}{4E}\right) \ . \tag{4}$$

We assume the oscillation is into τ-neutrinos, thereby restricting the electron survival probability to be one for both neutrinos and antineutrinos. As we only consider ν_μ to ν_τ oscillation there are no matter effects. The pathlength of the neutrino L is calculated using an average production point in the atmosphere of 15km. E is the neutrino energy.

The data are divided into sub-GeV and multi-GeV energy ranges and can be represented as the ratio, R^{exp}, between the experimental measured fluxes and the theoretical Monte Carlo prediction in the case of no oscillation. We define χ^2 as

$$\chi^2 = \sum_{M,S} \sum_{\alpha=e,\mu} \sum_{i=1}^{10} \frac{(R^{\mathrm{exp}}_{\alpha,i} - R^{\mathrm{th}}_{\alpha,i})^2}{\sigma^2_{\alpha i}} \ , \quad \alpha = \mu, e \quad i = 1 \dots 10 \ , \tag{5}$$

where $\sigma_{\alpha,i}$ are the statistical errors and M, S stand for the multi-GeV and sub-GeV data respectively and i is denoting the zenith angle bin. For the details of the χ^2 definition we refer to Ref.[6]. The overall normalization of the neutrino fluxes is allowed to vary freely. Hence we minimize with respect to α, where the neutrino flux is given by $\Phi = (1+\alpha)\Phi^0$. The theoretical predicted neutrino flux Φ^0 is taken from [14, 15]. In total we have five parameters (Δm^2_ν, $\Delta m^2_{\overline{\nu}}$, θ_ν, $\theta_{\overline{\nu}}$, α) and 40 data.

The minimum is $\chi^2_{\mathrm{min}} = 32$ at $\alpha = 0.04$ and

$$\Delta m^2_\nu = 1.7 \times 10^{-3}\,\mathrm{eV}^2 \ , \quad \Delta m^2_{\overline{\nu}} \gtrsim 0.1\,\mathrm{eV}^2 \ , \quad \sin^2(2\theta_\nu) = 1.0 \ , \quad \sin^2(2\theta_{\overline{\nu}}) = 1.0 \tag{6}$$

with 35 degrees of freedom. Note that this minimum is obtained for all values of $\Delta m^2_{\overline{\nu}}$ larger than 0.1 eV^2. The SK data becomes independent of the mass-squared difference in

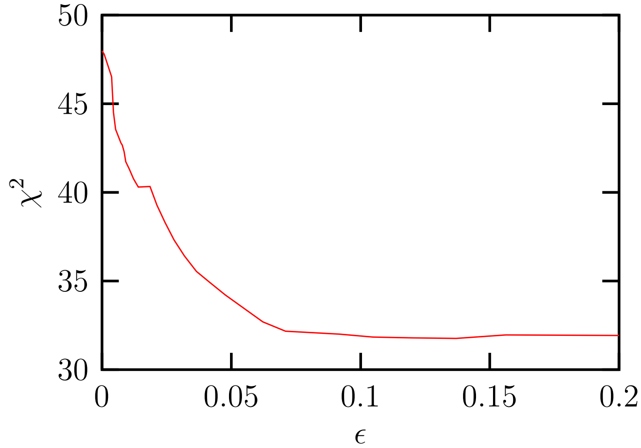

Figure 2: The minimum value of χ^2 as a function of the CPT violating parameter ϵ

this region as the oscillation probabilities are averaged to 1/2 for all pathlengths. In Fig.2 we show χ^2 as a function of ϵ when minimized with respect to all other parameter. For the CPT conserving scheme the best fit point is for $\chi^2_{\rm min} = 48$ at $\Delta m^2 = 3.0 \times 10^{-3}$ eV^2 and $\sin^2(2\theta) = 1.0$. This large difference in χ^2, $\Delta\chi^2 = 16$, seems alarming and should be interpreted with care. It is important to emphasize that in this analysis we have fixed the ν_μ/ν_e flux ratio to the theoretical predicted value. Allowing this ratio to vary give a substantial better χ^2 for the CPT conserving case as shown below. We would like to stress that this result should not be interpreted as CPT conservation is disfavored. The goodness of fit in the case of CPT conservation is high and therefore it is a valid explanation for the observed SK data. Another thing to mention is that when using confidence levels one relies on the fitted model being right. Although there are no direct experimental evidence against CPT violation for neutrinos there are many arguments against it from a theoretical perspective.

In Fig.3 we show the 90% and 99.7% confidence level as obtained by $\Delta\chi^2 < 9.2,\ 17.9$, respectively, for five degrees of freedom. The mass-squared difference for neutrinos is constrained within 4×10^{-4} eV$^2 - 6\times10^{-3}$ eV^2, while the antineutrino mass-squared difference is only bounded from below ($> 5\times10^{-4}$ eV^2). It is clearly seen that within the CPT violating frame the relation $\Delta m^2_{\overline{\nu}} \gg \Delta m^2_\nu$ is preferred. As an interesting curiosity this opens up the possibility to have the two antineutrino as well as the two neutrino mass-squared differences of the same order of magnitude in the Yanagida-Murayama model. At 90% CL the mixing angles are bounded as; $\sin^2(2\theta_\nu) > 0.9$ and $\sin^2(2\theta_{\overline{\nu}}) > 0.7$, but maximal mixing is preferred for both angles.

The predicted ratios of the best fit point are shown in Fig.4 along with the data points. The predicted ratio of around 0.85 for the downward going muon neutrinos can be easily understood. In this energy range the flux of neutrinos is roughly the same as the flux of antineutrinos. But the antineutrino cross section is less than half that of neutrinos. As the $\sin^2(L\Delta m^2/4E)$ is averaged to one half for antineutrinos and to one for neutrinos, we get the theoretical value around 0.85.

The great advantage of the CPT violating case is that it for a flux normalization that diminished the excess of in particular sub-GeV ν_e events also agrees well with the muon ratios. By rising the fluxes we lower the χ^2 from the ν_e-events. For mixing parameters around the best fit point a rise of the flux will also result in a lower χ^2 value for both sub-